

Aerial Survey of the Deschutes River, Washington

Thermal Infrared and Color Videography

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Report to:

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Final Report

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Introduction

In 2003, the Washington Department of Ecology contracted with Watershed Sciences, LLC (WS, LLC) to conduct an airborne thermal infrared (TIR) remote sensing survey on the Deschutes River, WA. The objective of the project was to collect TIR and color video imagery in order to characterize the thermal regime of the river. The imagery and analysis support Total Maximum Daily Load (TMDL) analysis.

Water temperatures vary naturally along the stream gradient due to topography, channel morphology, substrate composition, riparian vegetation, ground water exchanges, and tributary influences. Stream temperatures are also affected by human activities within the watershed. TIR images provide information about spatial stream temperature variability and can illustrate changes in the interacting processes that determine stream temperature. In most cases, these processes are extremely difficult to detect and quantify using traditional ground-based monitoring techniques.

It is the aim of this report to: 1) document methods used to collect and process the TIR images, 2) present spatial temperature patterns, and 3) highlight interesting features observed during image analysis. Thermal infrared and associated true color video images are included in the report in order to illustrate significant thermal features. An associated ArcView 3.2 GIS¹ database includes all of the images collected during the survey and is structured to allow analysis at finer scales.

Methods

Data Collection

The airborne survey of the Deschutes River was conducted on the afternoon of August 19, 2003. The river was flown upstream from Capitol Lake to Deschutes Falls, a distance of 42 miles (Figure 1).

Images were collected with TIR (8-12 μ) and visible-band cameras attached to a gyro-stabilized mount on the underside of a helicopter. The two sensors were aligned to present the same ground area, and the helicopter was flown longitudinally along the stream channel with the sensor looking straight down. Thermal infrared images were recorded directly from the sensor to an on-board computer in a format in which each pixel contained a measured radiance value. The recorded images maintained the full 12-bit dynamic range of the sensor. The individual images were referenced with time and position data provided by a global positioning system (GPS). The TIR images present a ground width of approximately 150 meters (494 ft) with a pixel size of 0.48 meters (1.54 ft).

A consistent altitude above ground level was maintained in order to preserve the scale of the imagery throughout the survey. The ground width and spatial resolution

¹ Geographic Information System

presented by the TIR image vary based on the flight altitudes. The flight altitude is selected prior to the flight based on average channel width and morphology. During the flight, images were collected sequentially with approximately 40% vertical overlap. The flight was conducted in the mid-afternoon in order to capture heat of the day conditions.

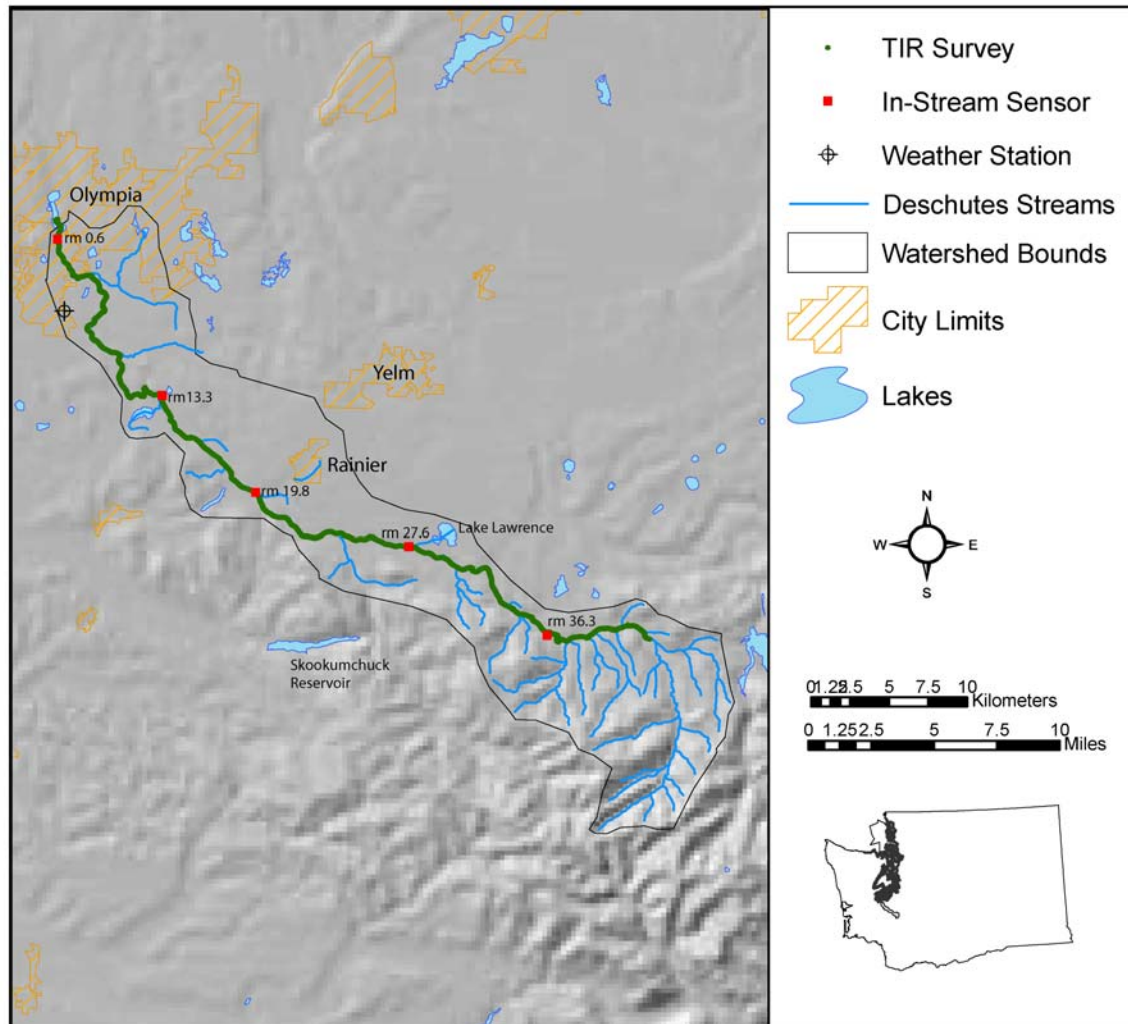


Figure 1 – Map showing the extent of the airborne TIR on the Deschutes River. The plot shows the location of the portable weather station and the location of in-stream sensors used to ground truth radiant temperatures derived from TIR images labeled by river mile (rm).

Prior to the flight, WS, LLC deployed in-stream data loggers in order verify the accuracy of the TIR data (i.e. ground truth). The in-stream data loggers were ideally located at intervals of 10 river miles or less over the survey route. Meteorological data including air temperature and relative humidity were recorded using a portable weather station (*Onset*) located at the Olympia Airport.

Data Processing

Measured radiance values contained in the raw TIR images were converted to temperatures based on the emissivity of water, atmospheric transmission effects, ambient background reflections, and the calibration characteristics of the sensor. The atmospheric transmission value was modeled based on the air temperatures and relative humidity recorded at the time of the survey. The radiant temperatures were then compared to the kinetic temperatures measured by the in-stream data loggers. The in-stream data were assessed at the time the image was acquired, with radiant values representing the median of ten points sampled from the image at the data logger location. Calibration parameters were fine-tuned to provide the most accurate fit between the radiant and kinetic temperatures.

Once the TIR images were calibrated, they were integrated into a GIS in which an analyst interpreted and sampled stream temperatures. Sampling consisted of querying radiant temperatures (pixel values) from the center of the stream channel and saving the median value of a ten-point sample to a GIS database file (Figure 2). The temperatures of detectable surface inflows (i.e. surface springs, tributaries) were also sampled at their mouth. In addition, data processing focused on interpreting spatial variations in surface temperatures observed in the images. The images were assigned a river mile based on a 1:100k routed GIS stream coverage from the Environmental Protection Agency (*Note: measures assigned from this coverage may not match stream measures derived from other map sources*).

The median temperatures for each sampled image of each surveyed stream were plotted versus the corresponding river mile to develop a longitudinal temperature profile. The profile illustrates how stream temperatures vary spatially along the stream gradient. The location and median temperature of all sampled surface water inflows (e.g. tributaries, surface springs, etc.) are included on the plot to illustrate how these inflows influence the main stem temperature patterns. Where applicable, tributaries or other features that were detected in the imagery, but were not sampled due to their small size (*relative to pixel size*) or the inability to see the stream through riparian vegetation are included on the profile to facilitate the interpretation of the spatial patterns.

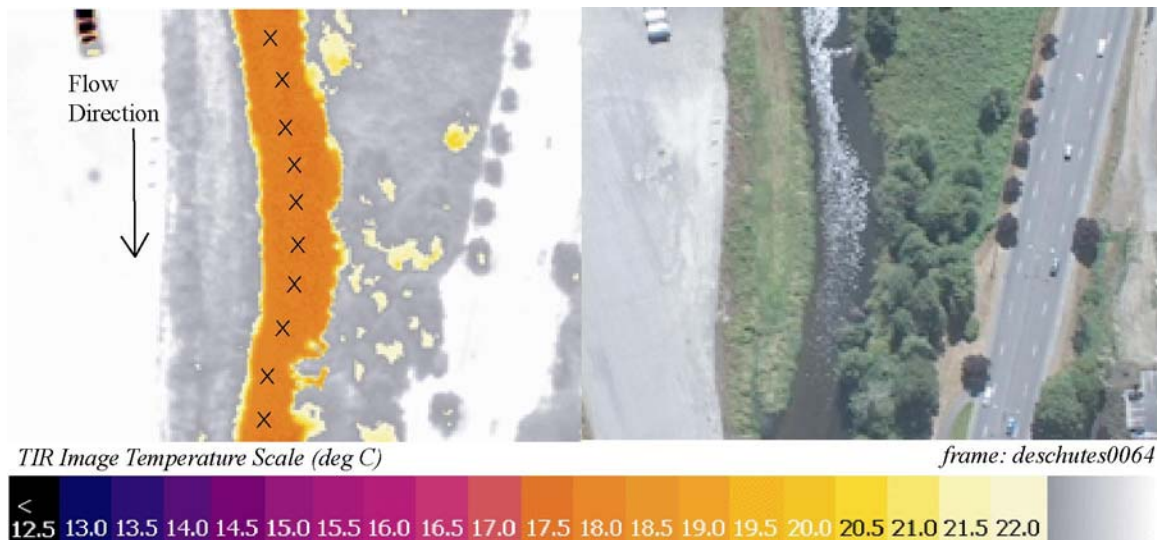


Figure 2 – TIR/color video image pair showing how temperatures are sampled from the TIR images. The black X's on the TIR image show typical sampling locations near the center of the stream channel. The recorded temperature for this image is the median of the sample points.

TIR Image Characteristics

Thermal infrared sensors measure TIR energy emitted at the water's surface. Since water is essentially opaque to TIR wavelengths, the sensor is only measuring water surface temperature. Thermal infrared data accurately represents bulk water temperatures where the water column is thoroughly mixed. However, thermal stratification can form in reaches that have little or no mixing. Thermal stratification in a free flowing river is inherently unstable due to variations in channel shape, bed composition, and in-stream objects (i.e. rocks, trees, debris, etc.) that cause turbulent flow. In the TIR images, indicators of thermal stratification include cool water mixing behind in-stream objects and/or abrupt transitions in stream temperatures. Occurrences of thermal stratification interpreted during analysis are identified in the results section for each survey.

Thermal infrared radiation received at the sensor is a combination of energy emitted from the water's surface, reflected from the water's surface, and absorbed and re-radiated by the intervening atmosphere. Water is a good emitter of TIR radiation and has relatively low reflectivity (approximately 4 to 6% of the energy received at the sensor is due to ambient reflections). During image calibration, a correction is included to account for average background reflections. However, variable water surface conditions (i.e. riffle versus pool), slight changes in viewing aspect, and variable background temperatures (i.e. sky versus trees) can result in differences in the calculated radiant temperatures within the same image or between consecutive images. The apparent temperature variability is generally less than 0.6°C (Torgersen et al. 2001). However, the occurrence of reflections as an artifact (or noise) in the TIR images is a consideration during image interpretation and analysis. In general, apparent stream temperature changes of $< 0.6^{\circ}\text{C}$ are not considered significant unless associated with a point source.

In stream segments with flat surface conditions (i.e. pools), relatively low mixing rates, or observed variations in spatial temperature patterns can be the result of differences in the instantaneous heating rate at the water's surface. In the TIR images, indicators of differential surface heating include seemingly cooler radiant temperatures in shaded areas compared to surfaces exposed to direct sunlight. Shape and magnitude distinguish spatial temperature patterns caused by tributary or spring inflows from those resulting from differential surface heating. Unlike with thermal stratification, surface temperatures may still represent bulk water conditions if the stream is mixed. Temperature sampling along the center of the stream channel (Figure 2) minimizes variability due to differences in surface heating rates. None-the-less, differences in surface heating combined with ambient reflection can confound interpretation of thermal features, especially near the riverbank.

A small stream width logically translates to fewer pixels “in” the stream and greater integration with non-water features such as rocks and vegetation. Consequently, a narrow channel (relative to the pixel size) can result in higher inaccuracies in the measured radiant temperatures (Torgersen et. al. 2001). In some cases, small tributaries were detected in the images, but not sampled due to the inability to obtain a reliable temperature sample.²

Results

Weather Conditions

Weather conditions for the times of the surveys are summarized in Table 1. Overall conditions were considered good for the TIR surveys with warm air temperatures and mostly clear skies.

Table 1 – Meteorological conditions recorded at Olympia Airport, WA on the afternoon of August 19, 2003.

Time 8/19/03	Air Temp. °F	Air Temp. °C	Relative Humidity %
13:00	75.2	24.0	48.9
13:30	75.9	24.4	47.4
14:00	78.0	25.6	41.2
14:30	80.8	27.1	35.7
15:00	80.8	27.1	31.8
15:30	81.5	27.5	32.8
15:55	83.0	28.3	37.7
16:00	83.7	28.7	40.7

² Features that are detected in the imagery, but not sampled for temperature are noted in the comment attribute of the flight point coverage.

Thermal Accuracy

Table 2 summarizes a comparison between the kinetic temperatures recorded by the in-stream data loggers and the radiant temperatures derived from the TIR images. The radiant temperatures matched the kinetic temperatures at the ground truth locations closely and were well within the desired accuracy of $\pm 0.5^{\circ}\text{C}$.

Table 2 – Comparison of ground-truth water temperatures (Kinetic) with the radiant temperatures for the survey of the Deschutes River, WA.

Image	Time	River Mile	Kinetic $^{\circ}\text{C}$	Radiant $^{\circ}\text{C}$	Difference $^{\circ}\text{C}$
<i>Deschutes R. 8/19/03 Avg. = 0.1°C</i>					
deschutes0055	13:42	0.6	17.6	17.7	-0.1
deschutes0713	14:04	13.3	19.5	19.2	0.3
deschutes0995	14:14	19.8	18.5	18.4	0.1
deschutes1367	14:26	27.6	19.4	19.5	-0.1
deschutes1842	14:42	36.3	18.8	18.9	-0.1

Temporal Differences

Figure 3 shows continuous in-stream temperature measurements in relation to the time of the TIR survey for two monitoring locations. Although not comprehensive, the plots provide some measure of when the TIR flight occurred in relation to the daily stream temperature maximum and provides a measure of temperature changes that occur during the time span of the flight. As shown, the flight was conducted just prior to the daily stream temperature maximums, which occurred between 15:25 and 16:15 at river mile 19.8 and between 15:50 and 16:23 at river mile 36.3. Water temperatures increased by 0.4°C during the course of the flight at river mile 19.8 and increased by 0.7°C at river mile 36.3. The influence of water temperature changes during the course of the flight is addressed in more detail in the *Discussion* section of this report.

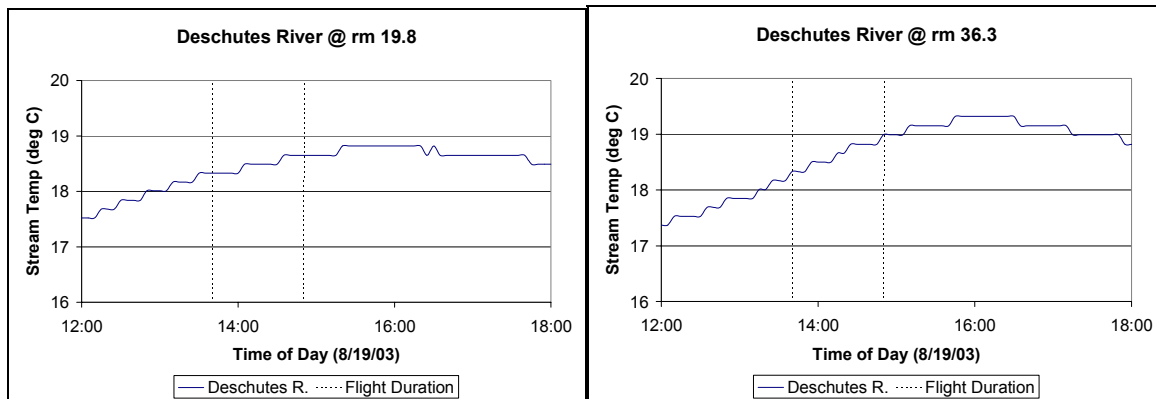


Figure 3 – Diurnal stream temperature variation during the afternoon of the TIR survey measured at two monitoring sites. The plots show the variations in relation to the time of the flight.

Longitudinal Temperature Profile

Median radiant temperatures were plotted versus river mile for the Deschutes River, WA (Figure 4). The location and name of sampled tributaries are illustrated on the plot by river mile and are listed in Table 3. Numerous apparent springs or small cool water seeps were detected while sampling temperatures along the Deschutes River. Several of these were not sampled for temperature due either to their small size or because they could not be positively identified in the imagery due to visible shadowing or vegetation. In order to facilitate visual interpretation of the spatial patterns, the location of these detected, but not sampled, cool areas were also plotted on the longitudinal temperature profile using the same temperature as the main stem. The longitudinal profile was also plotted in relation to in-stream temperatures both at the time of the over flight and the maximum daily temperature (Figure 5). At some locations, the data logger was retrieved prior to recording the daily maximum temperature and the in-stream temperature at the time of retrieval was plotted in lieu of the maximum temperature.

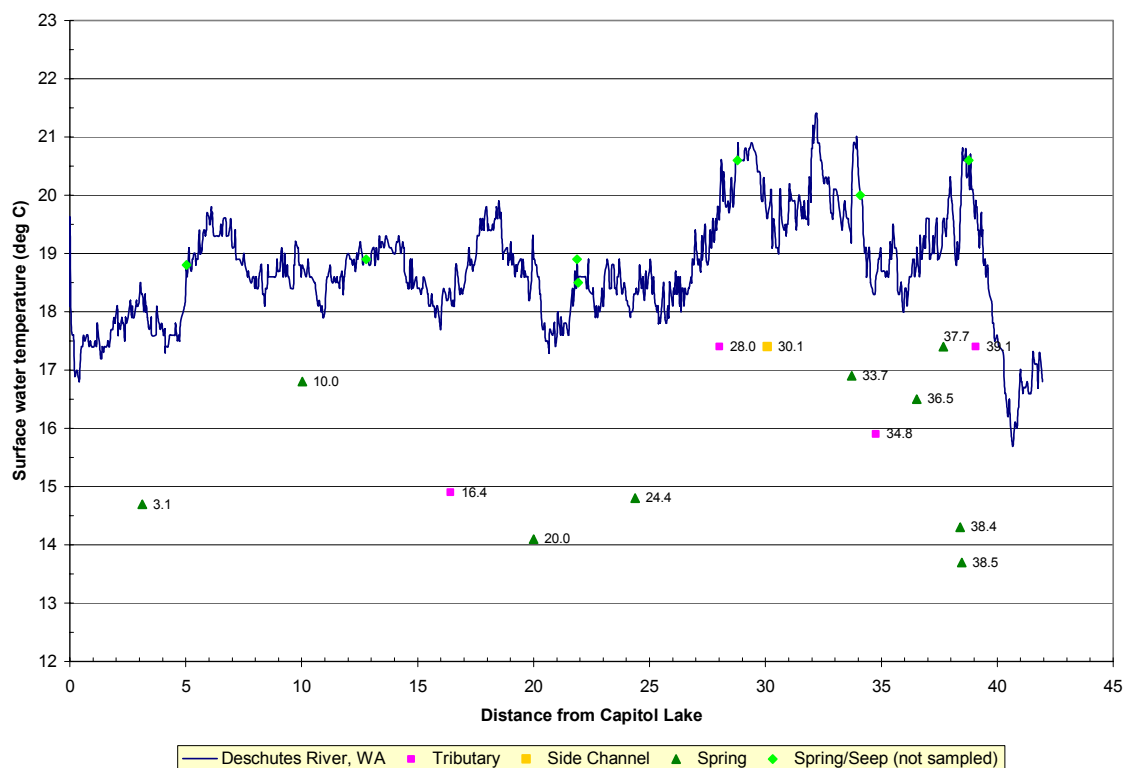


Figure 4 – Median stream temperatures plotted versus river mile for the Deschutes River, WA on August 19, 2003. The location of each surface water inflow is indicated by river mile.

Table 3 – Tributary and other surface water temperatures for the Deschutes River.
LB = left bank, RB = right bank looking downstream.

	Image	km	mile	Tributary °C	Deschutes R. °C	Difference °C
Tributary						
Silver Springs (RB)	deschutes0841	26.4	16.4	14.9	18.3	-3.4
Lake Lawrence Outlet (RB)	deschutes1379	45.1	28.0	17.4	19.6	-2.2
Fall Creek (LB)	deschutes1720	55.9	34.8	15.9	18.6	-2.7
Thurston Creek (LB)	deschutes1977	62.9	39.1	17.4	19.9	-2.5
Spring						
Spring/Seep (LB)	deschutes0178	5.0	3.1	14.7	18.3	-3.6
Spring/Seep (LB)	deschutes0524	16.1	10.0	16.8	18.8	-2.0
Spring (RB)	deschutes1000	32.2	20.0	14.1	18.9	-4.8
Spring (LB)	deschutes1193	39.2	24.4	14.8	18.3	-3.5
Spring (LB)	deschutes1626	54.3	33.7	16.9	20.1	-3.2
Spring/Seep (RB)	deschutes1852	58.8	36.5	16.5	19.1	-2.6
Spring/Seep (RB)	deschutes1900	60.6	37.7	17.4	19.6	-2.2
Spring (LB)	deschutes1939	61.8	38.4	14.3	19.7	-5.4
Spring (RB)	deschutes1943	61.9	38.5	13.7	20.5	-6.8
Side Channel						
Side Channel (LB)	deschutes1462	48.4	30.1	17.4	19.6	-2.2

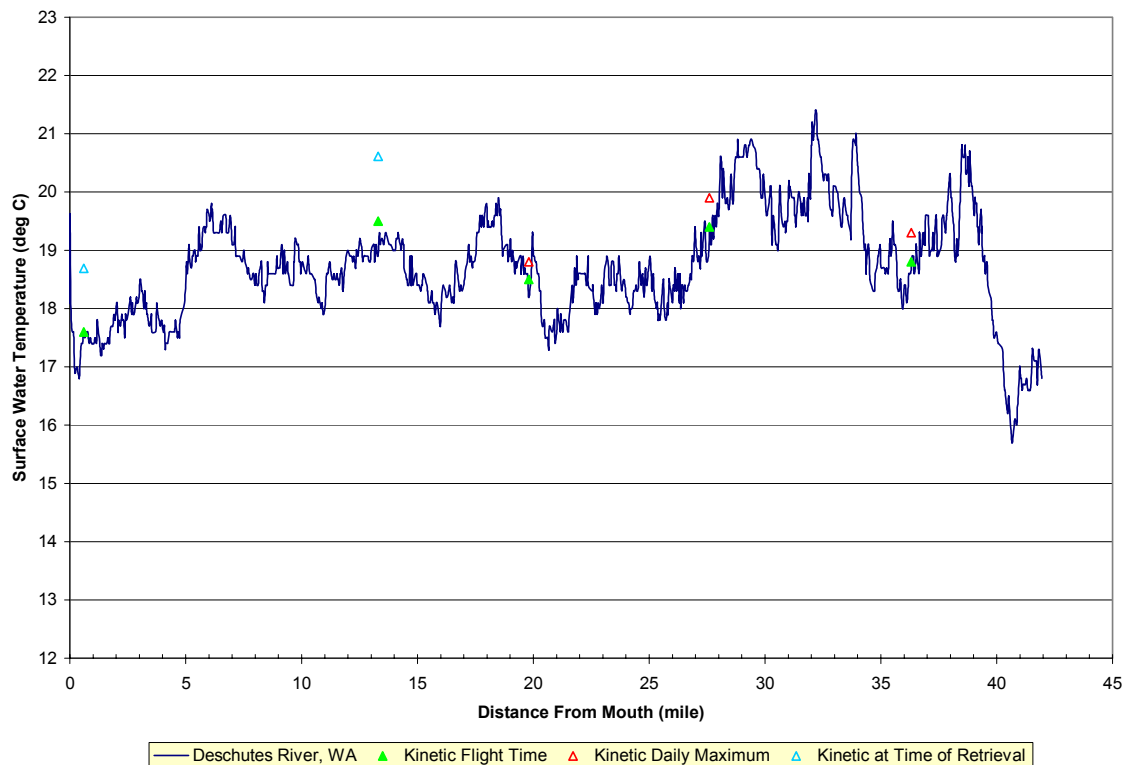


Figure 5 - - Longitudinal temperature profile derived from the TIR data plotted in relation to recorded in-stream (kinetic) temperatures. The temperature at the time the sensor was retrieved was plotted instead of daily maximum temperature at locations where the sensor was retrieved prior to recording the daily maximum temperature.

Overall, the Deschutes River exhibited a high degree of spatial thermal variability across multiple spatial scales. Visual inspection of the longitudinal temperature profile shows patterns of warming and cooling occurring at the reach and sub-reach scales. Four tributaries were sampled over the 42-mile survey extent and each contributed cooler water to the main stem. A total of 9 sub-surface inflows were sampled with an additional 8 suspected springs (or seeps) detected, but not sampled. The contribution of these cool water sources in defining spatial stream temperature patterns were often directly evident from the imagery. However, the detection of the sub-surface exchanges also provides an indication of the hydrologic processes (e.g. hyporheic flow) that are defining spatial temperature patterns at a broader scale.

At the upstream end of the survey, stream temperatures increased rapidly from $\approx 15.7^{\circ}\text{C}$ at river mile 40.7 to $\approx 20.6^{\circ}\text{C}$ at river mile 38.8. Radiant water temperatures declined over the next 2.8 miles reaching 18.0°C at river mile 36.0. Five inflows were detected through this reach, which contributed to the overall cooling trend. The localized thermal response from the two springs at river miles 38.4 and 38.5 is clearly apparent in the profile. Moving downstream, the profile shows a general warming trend with a relatively high degree of local variability. Local temperature maximums of 21.0°C and 21.4°C were observed at river miles 33.9 and 32.2 respectively. Both of these peaks were followed by rapid cooling. A spring inflow contributed at least in part to the cooling observed at river mile 33.9. However the source of cooling downstream of river mile 32.2 was not directly evident from the imagery. Inspection of the 1:24K topographic base maps shows that the apparent decrease occurs just downstream of the mapped valley of Lackamas Creek.

Between river miles 28.8 and 25.5, water temperatures in the Deschutes River decreased by $\approx 2.7^{\circ}\text{C}$. An apparent spring (not sampled) was detected at the upstream end of this reach and appeared to cool temperatures immediately downstream (Figure 6). However, the steady cooling trend (≈ 3.3 miles) is more indicative of a diffuse cooling source (i.e. shallow sub-surface exchange) throughout the reach or of a broader response to basin morphology than of a point source influence.

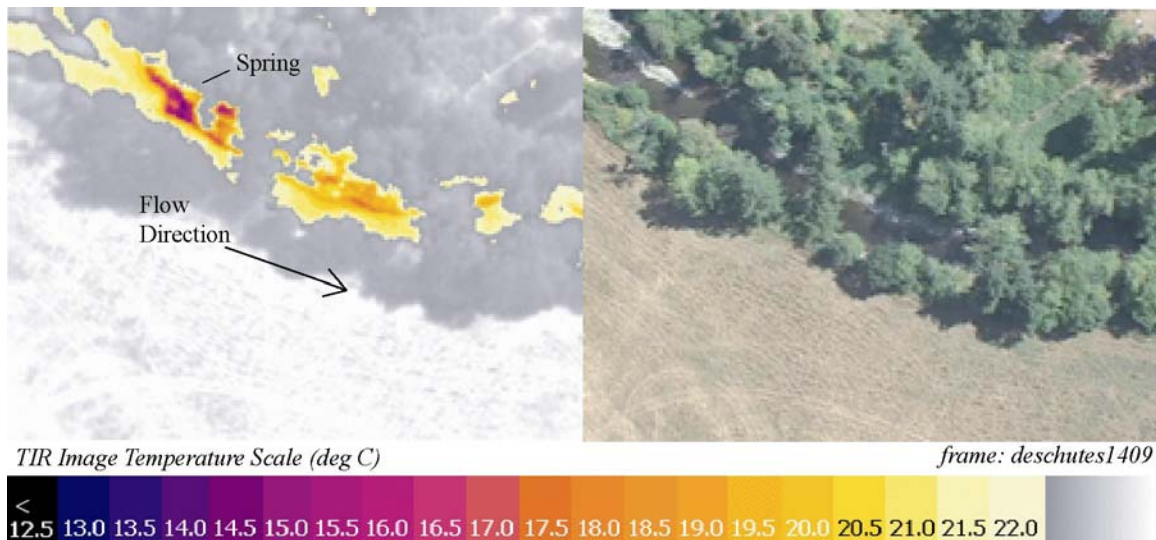
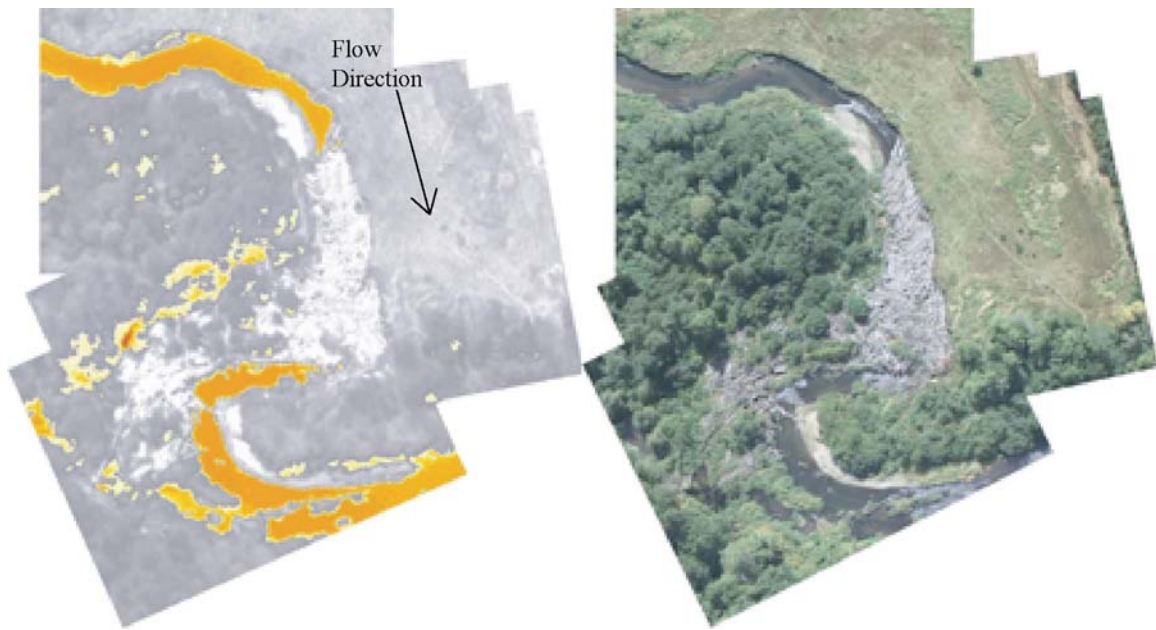


Figure 6 – TIR/color video image showing an apparent spring at river mile 28.8. The spring was not sampled for temperature due to the uncertainty created by the visible shadows. However, the longitudinal profile shows a local decrease in water temperatures downstream of this point.

From river mile 25.5 to river mile 5.3, water temperatures at the time of the survey varied between $\approx 17.3^{\circ}\text{C}$ and $\approx 19.9^{\circ}\text{C}$ with an overall sampled average of 18.7°C . Local variability was observed throughout this 20-mile river segment with detected spring or tributary inflows accounting for some of the variability. Further inspection of the longitudinal profile in relation to the in-stream sensors (Figure 5) shows a greater difference between the kinetic temperatures at flight time and the maximum daily temperature (*in this case the time of retrieval*) for the monitoring sites at river miles 0.6 and 13.3 than the sensors farther upstream. These differences suggest differential heating along the stream gradient. Consequently, one might expect a stretching of the profile towards higher temperatures later in the day especially in the lower reaches.

A log jam was detected in the Deschutes River at mile 5.3 (Figure 7). Downstream of the log jam stream temperatures decreased from $\approx 18.7^{\circ}\text{C}$ to $\approx 17.7^{\circ}\text{C}$. With the exception of the contribution of an apparent spring (not sampled) detected just downstream of the log jam, the source of cooling at this location was not directly evident from the imagery. One hypothesis might be that the log jam is forcing more water through shallow, sub-surface pathways. However, the actual source of cooling was not apparent from the imagery.



TIR Image Temperature Scale (deg C)

frame: deschutes0265-0271



Figure 7 - TIR/color video image pair showing a log jam at river mile 5.1 of the Deschutes River (18.8°C). A decrease in stream temperatures of $\approx 1.2^{\circ}\text{C}$ was observed within 0.3 miles downstream of the log jam.

Discussion

A TIR remote sensing survey was successfully conducted on the Deschutes River. A longitudinal temperature profile was produced, which illustrates broad scale spatial temperature patterns and the location and influence of tributary and surface water inflows. In-stream data loggers were distributed over the survey route and used to calibrate the TIR images and provide a measure of accuracy to the radiant temperatures.

This report offers some hypotheses on the factors contributing to the measured spatial temperature patterns based on interpretation of the imagery and visual inspection of the longitudinal profile. However, these hypotheses are intended as a starting point for more rigorous spatial analysis and field work. Additional analysis may include investigating spatial relationships between the observed temperature patterns and land-use, channel morphology, basin morphology, and vegetation. Additional field work may include verifying suspected ground water discharge points identified in the imagery. Individual TIR and color video image frames are organized in an ArcView database to allow viewing of the temperature patterns and channel characteristics at finer spatial scales.

The TIR images and derived data sets provide a spatially continuous data set for the calibration of reach and basin scale stream temperature models. Stream temperatures in the Deschutes River exhibited a relatively high degree of spatial variability across multiple spatial scales. Furthermore, basin scale temperature profiles did not follow generalized models of downstream warming with generally cooler temperatures observed in the middle and lower reaches than those observed upstream (i.e. river mile 30 to 40). Numerous springs and seeps detected during the survey indicate that sub-surface exchanges play a role in defining the thermal regime of the river. These data can therefore be useful in defining mass transfer points and improve the overall accuracy of the modeling effort.

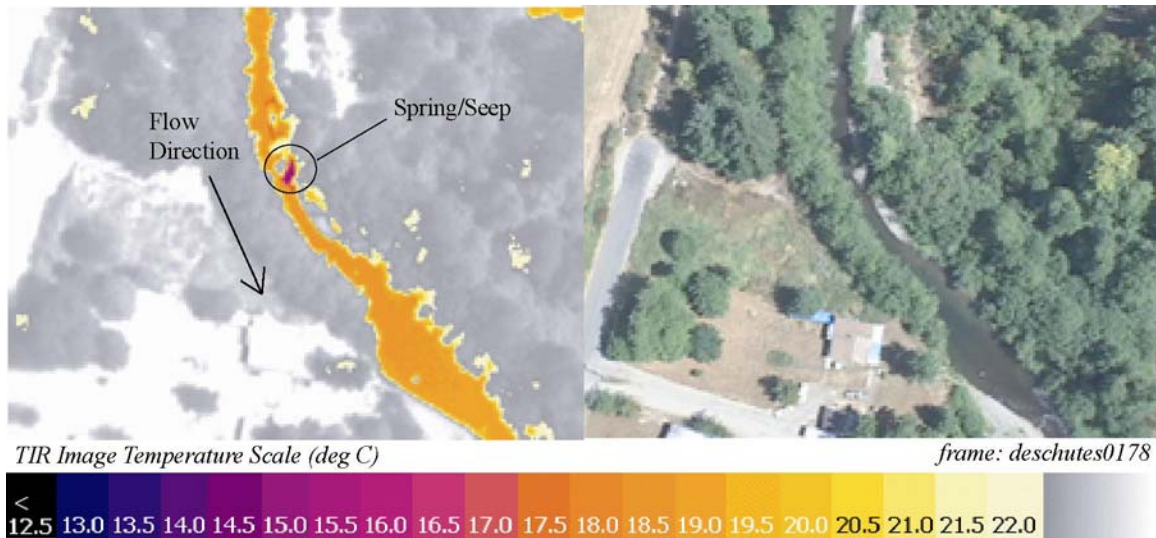
Bibliography

Faux, R.N., H. Lachowsky, P. Maus, C.E. Torgersen, and M.S. Boyd. 2001. **New approaches for monitoring stream temperature: Airborne thermal infrared remote sensing.** Inventory and Monitoring Project Report -- Integration of Remote Sensing. Remote Sensing Applications Laboratory, USDA Forest Service, Salt Lake City, Utah.

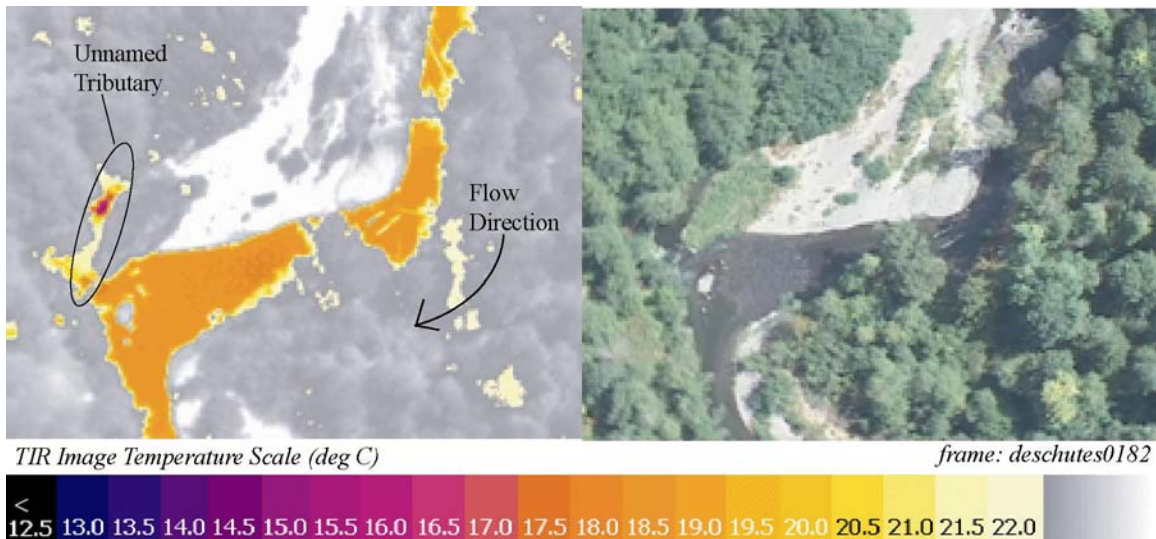
Torgersen, C.E., R. Faux, B.A. McIntosh, N. Poage, and D.J. Norton. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. *Remote Sensing of Environment* 76(3): 386-398.

Appendix A - Selected Images

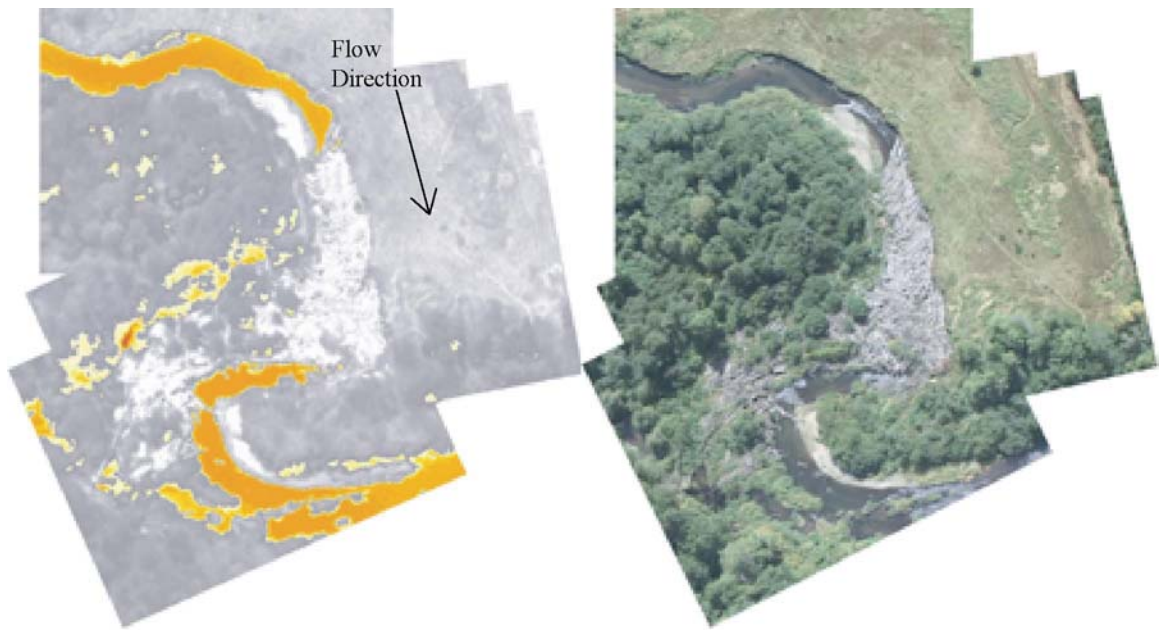
Left bank and right bank are referenced looking downstream. The flow direction is indicated, but is generally from the top to bottom of the image.



TIR/color video image pair showing an apparent spring/seep (14.7°C) along the left bank of Deschutes River (18.3°C) at river mile 3.1.



TIR/color video image pair showing an unnamed tributary (unsampled) along the right bank of Deschutes River (18.0°C) at river mile 3.2.



TIR Image Temperature Scale (deg C)

frame: deschutes0265-0271



TIR/color video image pair showing a log jam at river mile 5.1 of the Deschutes River (18.8°C)

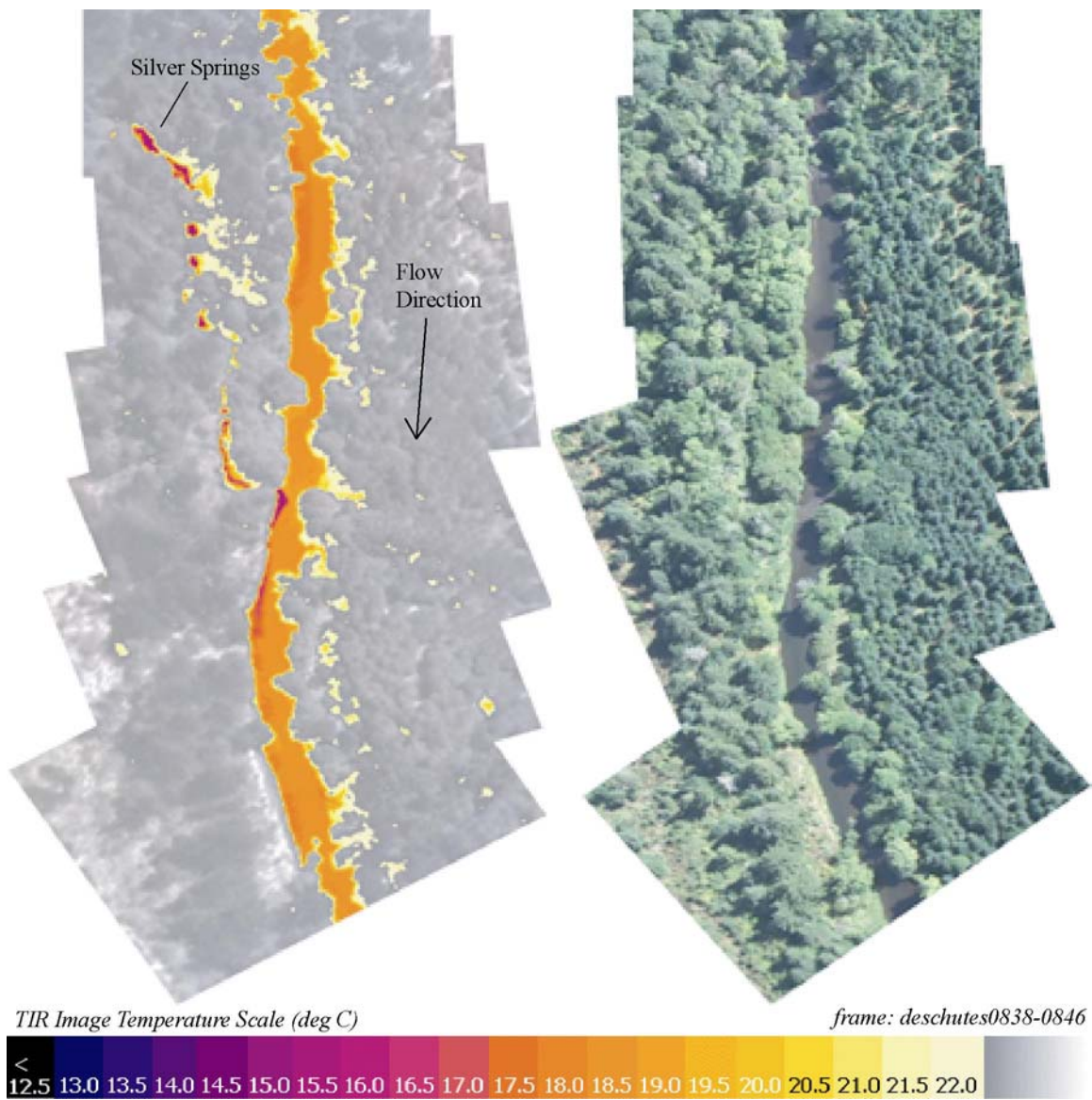


TIR Image Temperature Scale (deg C)

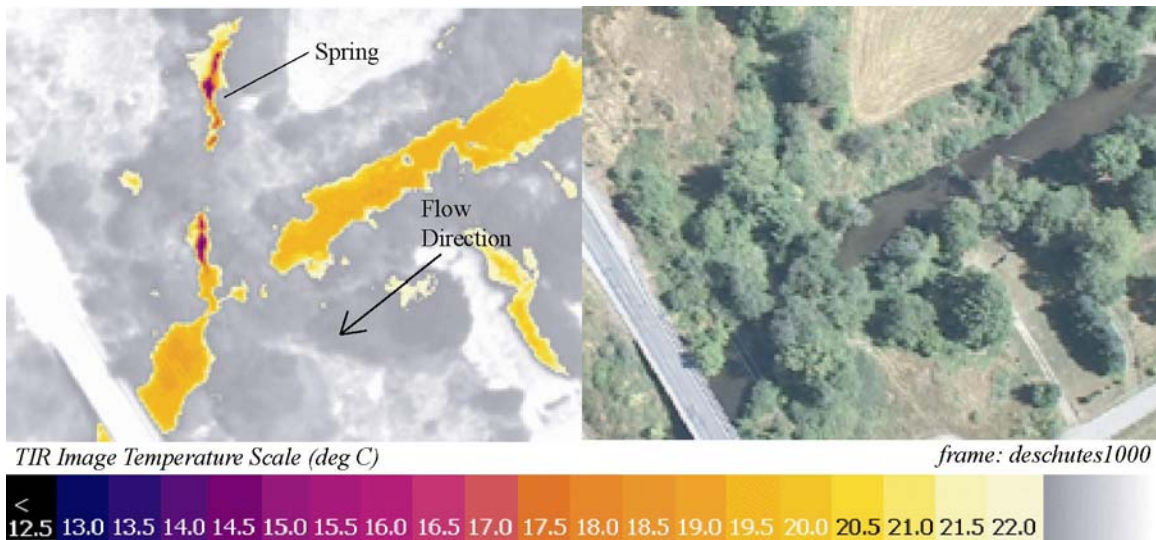
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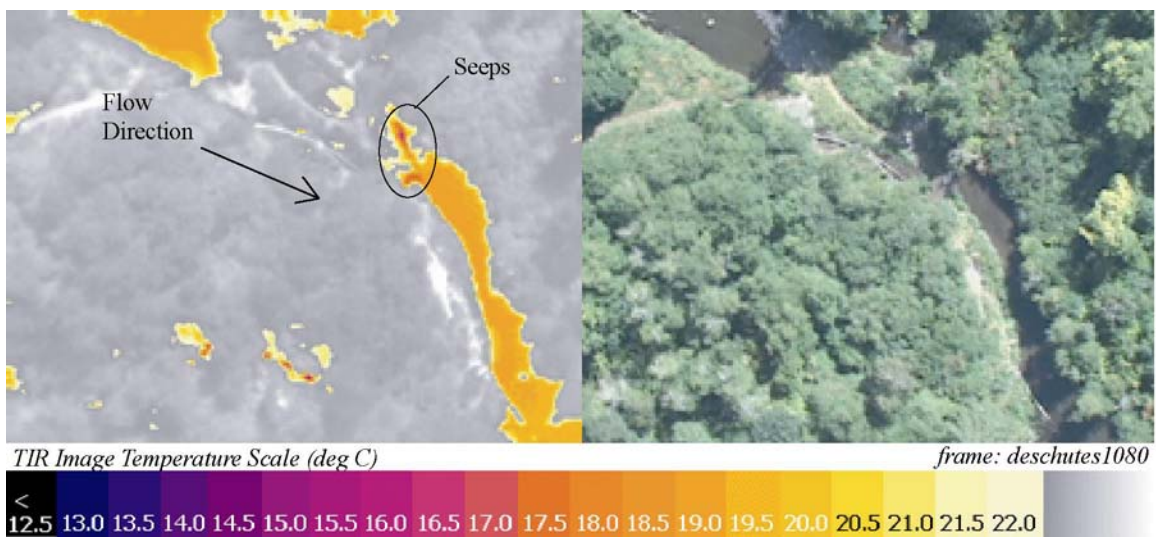
TIR/color video image pair showing an apparent spring (16.8°C) along the left bank of Deschutes River (187.8°C) at river mile 10.0.



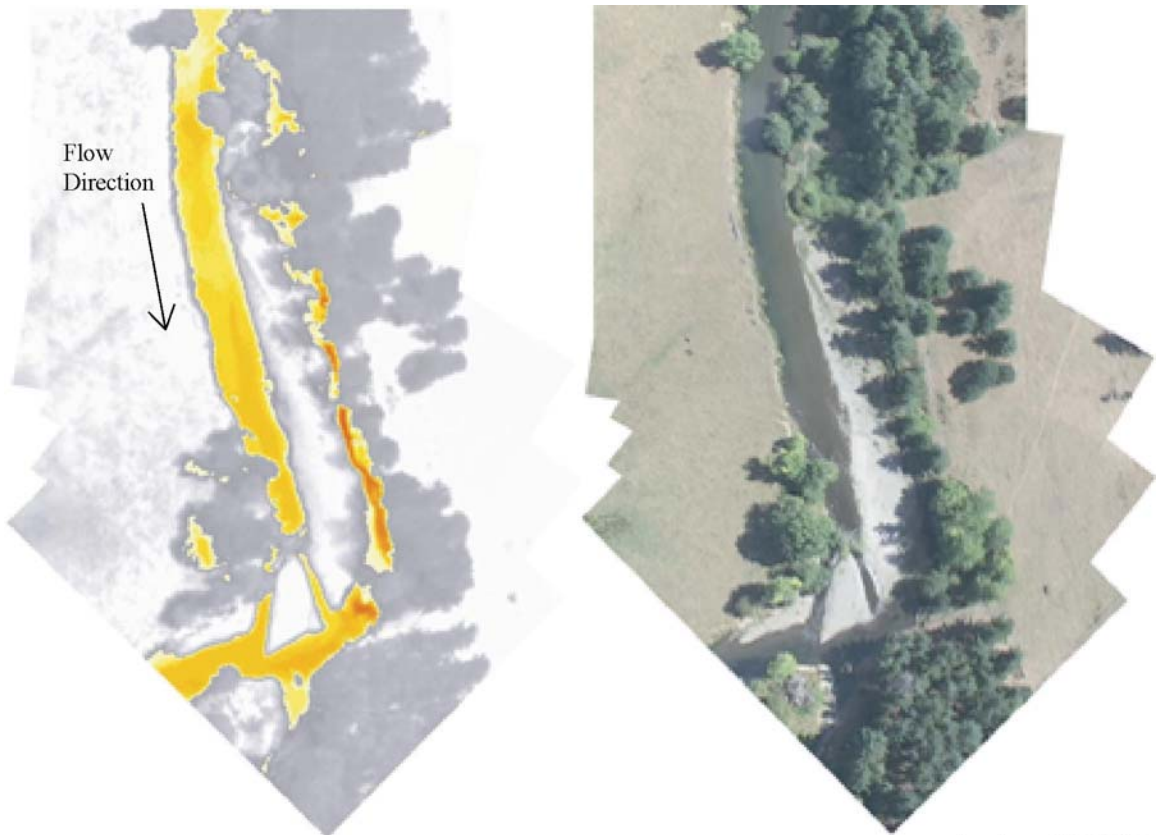
TIR/color video image pair showing the confluence of Silver Springs (14.9°C) to the right bank of Deschutes River (18.3°C) at river mile 16.4.



TIR/color video image pair showing a spring (14.1°C) on the right bank of Deschutes River (18.9°C) at river mile 20.0.



TIR/color video image pair showing two apparent seeps at the bottom of the gravel bar at river mile 21.9 of Deschutes River (18.9°C).

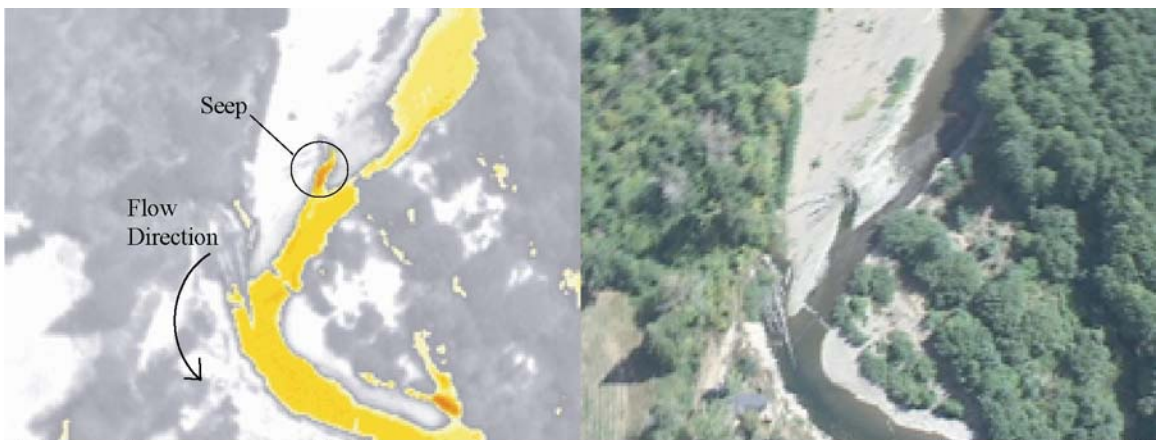


TIR Image Temperature Scale (deg C)

frame: deschutes1461-1465



TIR/color video image pair showing a cool side channel (17.4°C) along the left bank of Deschutes River (19.6°C) at river mile 30.1.

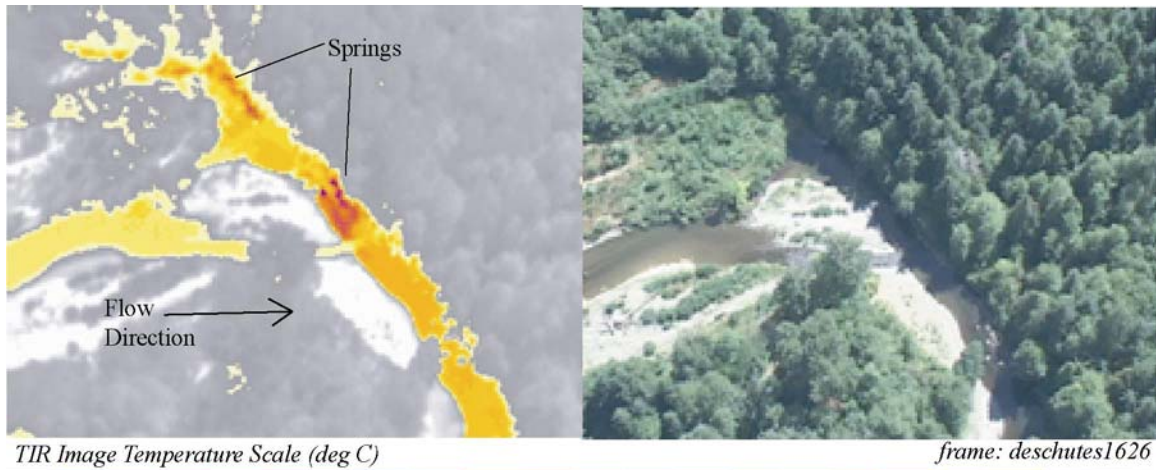


TIR Image Temperature Scale (deg C)

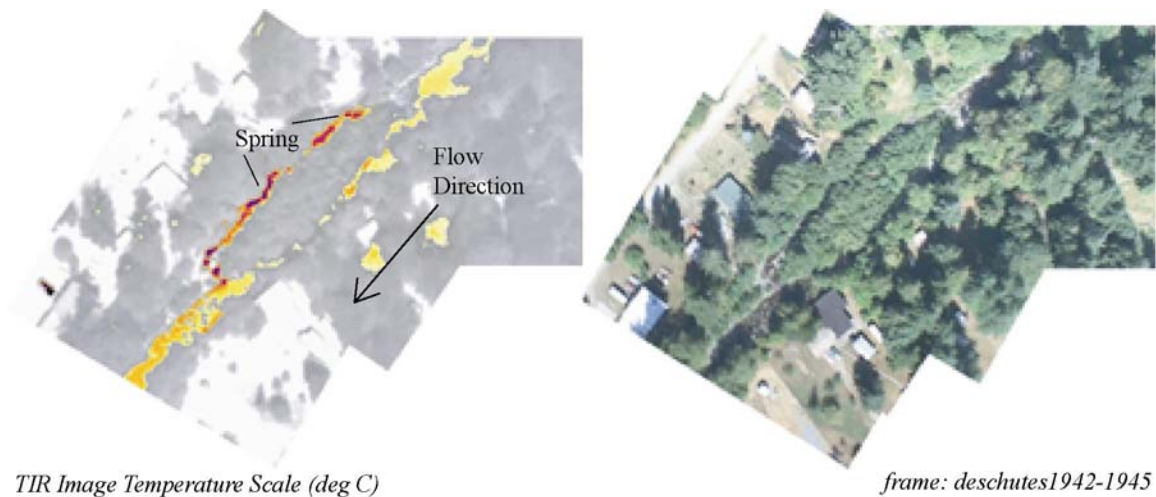
frame: deschutes1597



TIR/color video image pair showing a cool water seep along the right bank of Deschutes River (20.1°C) at river mile 33.0.



TIR/color video image pair showing two apparent springs (16.9°C) along the left bank of Deschutes River (20.1°C) at river mile 33.7. Radiant water temperatures decreased by $\approx 1.5^{\circ}\text{C}$ immediately downstream of this location.



TIR/color video image pair showing a spring (13.7°C) along the right bank of Deschutes River (20.5°C) at river mile 38.5.